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Combined fluvial and pluvial flood inundation modelling for a project site

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Abstract

There are many sources of flooding viz. river flooding, coastal flooding, surface water flooding, drain and sewer flooding, groundwater flooding etc. This study envisages identification of various flooding sources, estimation of maximum floods and their routing through drainage system for a proposed industrial site. The digital elevation model (DEM) is developed from DGPS points, 0.5 m interval contour and spot levels and contours extracted from survey of India topographical maps for the surrounding area. The L-moments based rainfall frequency analysis has been performed to estimate 1 day maximum rainfall for various return periods. The synthetic unit hydrographs are derived from catchment characteristics and flood hydrographs for 10, 25, 50 and 100 year return periods are computed. The two major source of flooding are: flow in the drain and rainfall induced catchment flooding are modelled using MIKE FLOOD package. The bathymetry of the flood plain around the plant site at 5 m grid size is created from DEM in the 2-D modelling in MIKE-21. Local rainfall over the proposed industrial site is also modelled in the MIKE-21. The spills from drainage network due to upstream catchment flow and local rainfall are simulated in coupled MILE-11 and MIKE-21 i.e., MIKE FLOOD package. Various scenarios of flooding like flow in the drain and with and without rainfall of various return periods are simulated to develop corresponding flood inundation maps. Other parameters like flood extent, depth, level, duration and maximum flow velocity are also computed. The safe grade levels for the industrial site are proposed considering these parameters to safe guard the flood disaster.

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Keywords: pluvial and fluvial flooding; flood frequency analysis; hydraulic modelling; flood hazard assessment

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1. Introduction

Floods are one of the common and widespread of all natural disasters happening frequently over the globe. India is among the highly flood prone countries in the world due to various types of flooding like river flooding, coastal flooding, surface water flooding, drain and sewer flooding, cloudburst flooding etc. India receive high amount of rainfall in monsoon seasons, frequently causing pluvial floods in combination with embankment breach and riverine floods. In general, fluvial flood events considerably differ from pluvial (rainfall) flood events both in spatio-temporal scale including its magnitude. The fluvial events usually occur for duration of days, or even weeks with widespread damages in the floodplains of river system. On the other hand, pluvial flooding hardly ever happens for more than one day duration with influence on local regions. Whatever be the type of flooding, it causes huge losses in terms of tangible losses viz. damage to buildings with their contents; industrial facilities; rail and road network; other infrastructures; and intangibles losses due to business interruption causing huge economic losses, apart from loss of human lives. The impact of flood event can be limited to very local scale affecting a locality or society; to very large, affecting entire river basin with various districts and states. With time it has been realised that it is not possible to fully prevent flood disaster, however with adoption of suitable structural and non-structural measures and appropriate planning the losses due to flood can be minimized to certain extent. Flood inundation modelling plays a very important role for mitigating and reducing losses due to flood hazard by advance prediction of flood characteristics like its extent, depth, duration, velocity etc. These flood characteristics are used for development of flood hazard maps and also help in flood plan zoning [1]. Over the past decade significant advancement have been taken place in terms of development of 1-D and 2-D hydrodynamic models, satellite and remote sensing data products etc causing large improvement in the efforts towards flood inundation modelling and hazard assessment. Progress has also been made in the understanding of various processes controlling runoff and flood wave propagation, hydrologic and hydraulic simulation techniques with uncertainty handling, affordable high power computing facilities etc.

The most appropriate method for flood hazard assessment is a combination of hydrologic and geomorphologic approach [2][3][4][5]. The flood hazard maps are produced by simulation of detailed hydrological and hydraulic models with probabilistic rainfall and discharge analysis. These models are forced and parameterized by locally available, high resolution and preferably high quality spatio-temporal data. The hydrological-hydraulic mechanisms integrated with GIS approach for modelling of flood provides, systematic and consistent analyses of flooding together with their likelihood of occurrence in a given time period. The hydraulic packages solve 1D (river/drain) and 2D (overland) shallow water equations considering the topography of area. The combination of GIS and 1D hydrodynamic modelling may provide a cost efficient system for planning and management of flood.

Various researchers have applied coupled 1-D channel and 2-D overland flow models for simulating flow dynamics between rivers/ drains and floodplains for fluvial flood inundation modelling, [6][7][8][9]. In such aapproaches the flow in channel and overland are routed separately by solving 1-D and 2-D Saint-Venant's equations and linking them with structures like weirs or pumps. Modelling hydrodynamic channel flow in river or drain in conjunction with a full 2-D hydrodynamic model in order to describe the surface flow are very essential and described by many researchers [10][11][12]. In pluvial flooding studies, the 1-D channel flow models are developed to simulate interactions among various sub-catchments, and between the surface and sub surface flow [13][14]. The overland flow from channel system occurs when the runoff caused by pluvial events is higher than major channel capacity. In such scenario when the flow is no longer confined to predefined flow paths, the 1-D modelling approaches are believed to be inadequate to capture the process. Under such situation, 2-D overland flow models are required for better prediction of flood propagation. Therefore, a coupled 1-D channel and 2-D overland flood inundation models, which consider the interactions between channel and flood plain, are the best method to study details of overland flow propagations [15][16]. Recently, commercial software such as SOBEK, XP-SWMM 2D and MIKE FLOOD etc. provides various options for integrating 1-D channel and 2-D overland flow modelling functionalities in their packages.

Practically, pluvial flooding frequently occurs along with fluvial flooding, intensifying catastrophic consequences than that may be caused due to occurrence of a single type of flooding separately [17]. Hence, there is need to study them together in an integrated dynamic modelling platform to assess all potential drivers with their combined effects. In this paper, we have analysed the possible flood inundation for a proposed industrial site due to a combination of overflow of drain and rainfall of various return periods using coupled 1-D &2-D MIKE FLOOD package, which includes MIKE-11 and MIKE-21 applications. The state of art flood frequency analysis based on the L-moments is used to select best fit distribution among 12 frequency distributions for estimation of various return periods floods.

2. Study area and data

The proposed plant/industrial area is located in northern India as shown in Fig. 1. One major drain flows through the proposed plant boundary from north to south direction and two other small drains joint from both side. One highway also passes through the proposed plant boundary (Fig. 1). There are two culverts in highway, to drain the runoff generated from the west side of highway area and join to main drain. The general topography of the area is very flat terrain, mostly covered with uncultivated land and brick kiln area. The geographical area of the plant site is about 6 km2. The climate is extreme and tropical with average temperature in summer and winter season is 33.52°C and 14.33°C respectively. The normal annual rainfall in the area is about 673.5 mm.

Daily rainfalls for three rain gauge stations surrounding plant area are obtained from India Meteorological Department (IMD) for rainfall frequency analysis. The topographic survey in the proposed plant area was carried and cross-section of drains were also measured (Fig. 2). The bathymetry is prepared from these surveyed contours, SRTM DEM and contour and spot height of SOI toposheet.

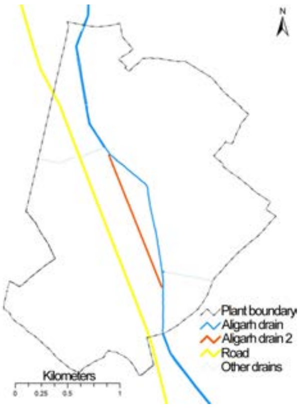

Fig. 1. Location of the proposed industrial area with road and drains.

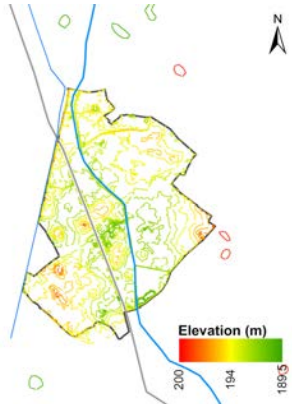

Fig. 2. Topography of the study area.

3. Methodology

The methodology adopted in the study mainly consists of design flood estimation for various return periods and development of a coupled 1-D & 2-D flow model for drain network and flood plain respectively.

3.1 L-Moments Based Rainfall Frequency Analysis

Regional rainfall frequency analysis of 1-day annual maximum rainfall values of three raingauge stations lying within and near study area has been carried out using the L-moments approach as described elsewhere (Hosking and Wallis 1997; Kumar and Chatterjee 2005). Twelve frequency distributions viz. extreme value (EV1), general extreme value (GEV), logistic (LOS), generalized logistic (GLO), normal (NOR), generalized pareto (GPA), generalized normal(GNO), uniform (UNF), exponential (EXP), pearson Type-III (PT3), kappa (KAP) and wakeby (WAK) have been used to identify robust distribution based on the L-moment ratio diagrams and the Z_i^{dist} –statistic criteria. The details about these distributions and relationships among parameters of these distributions and L-moments are available in literature [18].

3.2 Derivation of Synthetic Unit Hydrograph

Initially a wide extent of generated DEM has been used to delineate the drainage network in and around the proposed plant area. The HEC-GeoHMS 5.0 package in ArcGIS 9.3 is used for automatic delineation of catchments from DEM. The main drain is a natural drain and maintained by Irrigation Department and there are number of irrigation canals and road with culverts in the catchment area of drain. Moreover, the catchment area is comparatively small with very flat topography. Hence, automatic delineation of catchments from DEM was not very accurate. In such case the catchment area is delineated manually from the SOI topsheets considering the topographic features. However, the 2 h SUH is developed for the larger area using catchment characteristics and flood estimation report [19]. Then 1 h SUH, is derived using S-curve technique.

3.3 Estimation of Design Flood Hydrographs

The manual on estimation of design flood [20] analyzed time distribution pattern of storms in the area for which adequate self recoding rain-gauge data are available. In the manual, depth duration analyses of maximum rainfall depths for standard duration of 6, 12, 18, 24, 36, 48 hours etc., were obtained for each of the storms and expressed as percentage of the total storm depth. Enveloping percentages are then obtained and applied to adjust the design rainfall based on observational data. In absence of hourly rainfall data it is recommended to apply a factor of 1.15 to convert 1-day maximum rainfall to 24-h maximum rainfall. The 24 hour rainfall is divided in to incremental hourly rainfall according to time distribution provided in the [19] report. To obtain the critical sequence of rainfall the largest of increments is placed against the peak of UH, then the next largest against the next UH ordinate and so on until all rainfall increments get arranged. Then the sequence is reversed to get the critical sequence for all spells. In case of 24-h duration rainfall the first and second 12 h blocks are interchanged to get critical situation. The design loss rate is subtracted from the hourly rainfall to obtain effective rainfall hyetograph and then direct runoff hydrograph is estimated by convoluting this effective rainfall with SUH. Finally, the base flow is added to obtain design flood hydrograph. The design flood hydrograph for drain is estimated as proportion to their catchment area.

3.4 Flow Simulation and Flood Modelling

The flow in drain and rainfall induced catchment flooding has been modelled MIKE 11 and MIKE 21 model respectively. The MIKE 21 has been dynamically linked to the MIKE 11 model, into a single package called MIKE FLOOD developed at the Danish Hydraulic Institute [21] is widely used for flood inundation studies.

3.5 Flow modelling by Mike 11 hydrodynamic model

MIKE 11 is a versatile and modular engineering tool for modelling hydrodynamic conditions in rivers, open channel, irrigation canals and other inland water systems. It includes full solution of the Saint-Venant equations which is very usefull for the detailed analysis, design, management and operation of both simple and complex river and channel systems [22]. The hydrodynamic model is the nucleus of the MIKE 11 modelling system and forms the basis for simulation of flood inundation. The governing equations in MIKE 11 are 1-D and shallow water type, which are the modifications of basic Saint-Venant equations. These are transformed to a set of implicit finite difference equations, and solved using double sweep algorithm [23]. The computational grid comprises of alternating Q and H points automatically generated by the model, on the basis of user requirements. Q points are always placed midway between neighbouring H points. The maximum space interval, i.e. dx=100 m is used the present setup. The drain cross-sections are specified by a number of x-z co-ordinates where x is the transverse distance from a fixed point (often left bank top) and z is the corresponding bed elevation. The x-z co-ordinates are entered as raw data in the cross-section editor. The upstream boundary condition for drain is given as design discharge and stage discharge relationship for downstream boundary condition. The HD parameters, in the present study, include the initial conditions of water level and discharge, friction coefficient (n) and output parameters options. Initial conditions are required to avoid the dry bed conditions. The n value is specified as 0.033. The global value for the initial condition for water level is kept at a low value of 0.01m to avoid dry bed condition. The time step is kept very low as 2 second with the dx value of 100 m. The simulation has been performed for 48 h period.

3.6MIKE Flood model set up

For the simulation of MIKE FLOOD, MIKE 21 set up is required, because the former is a coupled unit of both MIKE 11 and MIKE 21 simulations. In the present study, parameters defining bathymetry, precipitation, initial surface elevation, flood and dry thresholds have been used. The resolution of the prepared bathymetry is 5 m × 5 m. The computational time step (Δt) is set to lower value of 2 seconds for different simulations. The prepared MIKE 21 setup, in the present study, is executed to check error. MIKE FLOOD couples MIKE 11 and MIKE 21 into a single system. Using this coupled approach, MIKE FLOOD enables to extract best features of both MIKE 11 and MIKE 21 flood inundation simulation, while at the same time avoiding many of the limitations of resolution and accuracy encountered when using MIKE 11 or MIKE 21 separately. The lateral link allows a string of MIKE21 cells to be laterally linked to a given reach in MIKE 11, either a section of a branch or an entire branch. Flow through the lateral link is calculated using a weir equation or a Q-H table. This type of link is particularly useful for simulating overflow from a river channel onto a floodplain, where flow over the river levee is calculated using a weir equation. The structure link takes the flow terms from a structure in MIKE 11 and inserts them directly into the momentum equations of MIKE 21. The zero flow link is defined to prohibit the flow across the cell in a particular direction of X or Y. The girded hourly rainfall are also provided in the MIKE 21 model setup.

4. Results and Discussions

4.1 Rainfall Frequency Analysis

Rainfall frequency analysis has been carried out using the L-moments approach. The Generalized Extreme Value (GEV) is identified as robust frequency distribution for the study area based on Zi dist statistic (table 1) and L-moment ratio diagram (Fig. 3). The parameters of various distributions for 1-day maximum rainfall are also given in table 1. The growth factors or site-specific scale factor ($R_T/\bar{R}$) are computed by dividing rainfall quantile (R_T) by the annual mean maximum rainfall. The 1-day maximum rainfall for various return periods are estimated by multiplying the respective growth factor with mean annual maximum rainfall. The estimated 1-day maximum rainfall for 10, 25, 50 and 100 year return period area 160.4mm, 207.1 mm, 246.5 mm and 289.9 mm respectively.

Table 1. Z_i^{dist} – Statistic of various distributions with parameters for 1-day annual maximum rainfall.

Distribution	**Z_i^{dist} –statistic**	**Parameters of the Distribution**		
Generalized Extreme Value (GEV)	**-0.30**	ξ = 0.749	α = 0.332	K = -0.153
Generalized Normal (GLO)	0.31	ξ = 0.883	α = 0.239	k = -0.272
Generalized logistic (GNO)	-0.67	ξ = 0.871	α = 0.420	k = -0.566
Pearson Type III (PE3)	-1.30	μ = 1.000	σ = 0.521	γ = 1.634

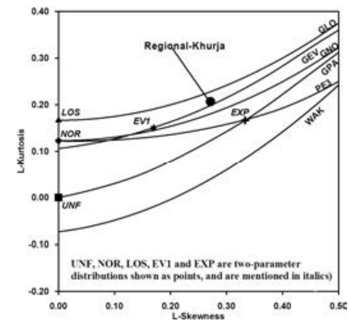

Fig. 3. L-moments ratio diagram for 1-day annual maximum rainfall.

4.2 Design Flood Hydrographs

The synthetic unit hydrograph derived from catchment characteristics and relationships given in flood estimation report for a catchment area of 10.5 km^2 is shown in figure 4. After applying clock hour correction the 2, 10, 25, 50 and 100 year return period 24-h maximum areal rainfalls are found to be 9.83 cm, 18.45 cm, 23.82 cm, 28.35 cm and 33.35 cm respectively. The time distribution of rainfall was adopted according to the CWC report [19]. Base flow has been estimated at a rate of 0.05 m3/s/km2 for the catchment area and added to estimated direct runoff hydrograph for estimating flood hydrographs. The Peak flood for 2, 10, 25, 50 and 100 year return periods are found to be 20.13 m3/s, 44.06 m3/s, 59.1 m3/s, 71.59 m3/s and 85.88 m3/s respectively and the flood hydrographs are shown in figure 5.

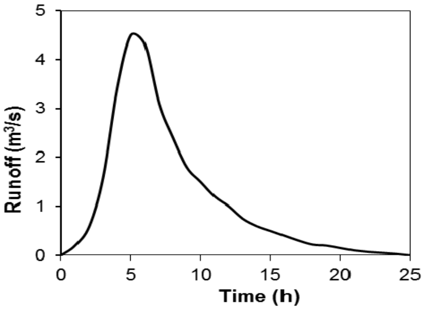

Fig. 4. 1-h synthetic unit hydrograph

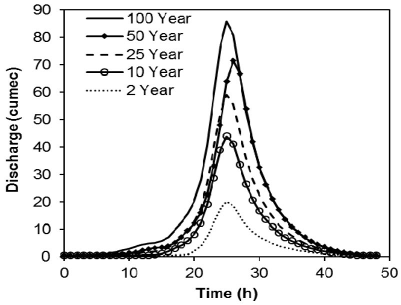

Fig. 5. Design flood hydrographs for various return periods due to 1-day rainfall for various return periods.

4.3 Flood Inundation Modelling

To study the effect of local rainfall of various return periods and corresponding flow in the drain MIKE 11 setup is coupled with MIKE 21 setup. The bathymetry of plant area is prepared at 5 m grid size for MIKE FLOOD simulation. The flooding extent and flood water depths in the plant area due to combined event of overflowing of drains and local catchment rainfall of various return periods are shown in figure 6. It is observed that there are overtopping of drain in all sections. Seven grids (cross marked in figure 6(a)) are selected on both sides of drain to analyze detail time series of flood depth. The water depth and water levels at these grids for 100 year return period flood are shown in figure 7. It can be noticed that the maximum water level at most upstream grid attains maximum water level of 193.3 m and in all other cases the maximum level is below 193.1 m. The water levels for various return periods during 48 hour simulation period at the grid point 1 are shown in figure 8. It is observed that the maximum flood depth is 30 cm and total flooding duration is about 12 hour for 10 year return period at grid point 1. The maximum death of flooding increase to 60 cm from 30 cm for 100 year return period. There is increase in both flood extent and duration for higher return period floods. Though there is variation in depths of flooding in upstream and downstream reaches, the duration of flooding are identical.

5. Conclusions

The flooding due to overflow of drain and catchment rainfall for various return periods are studied for a proposed industrial site in northern India. Regional rainfall frequency analysis is carried out using L-moments approach to estimate 1-day maximum rainfall for various return periods. After applying clock hour correction the estimated 2, 10, 25, 50 and 100 year return period 24-h maximum areal rainfalls are found to be 9.83 cm, 18.45 cm, 23.82 cm, 28.35 cm and 33.35 cm respectively. The DEM of study area is prepared from GPS points, 0.5 m interval contour maps and levels and contours extracted from survey of India topographical maps. The synthetic unit hydrographs are derived from catchment characteristics of the study area and flood hydrographs for 10, 25, 50 and 100 year return periods are computed. Flow through the drainage system is modelled in MIKE 11 with a space interval of 100m to get accurate representation of the drainage network. The bathymetry of the flood plain around the plant site at 5m grid size is created from DEM in MIKE-21. Local catchment rainfall over the proposed industrial site is also modelled in the MIKE-21. The spills from drainage network and local rainfall are simulated in MIKE FLOOD package. The flood inundations for various return periods are simulated in MIKE FLOOD to develop corresponding flood inundation maps. It is observed that there is overtopping of drain is in all sections. At seven grids points on both sides of drain detail analysis of time series of flood water depth is performed. The maximum water level at upstream grid attains maximum level of 193.3 m and in all other cases the maximum level is below 193.1 m for 100 year return period. The maximum flood depth is 30 cm for a flooding duration of about 12 hour for 10 year return period at grid point 1 and increase to 60 cm for 100 year return period. It is observed that there is increase in both extent and duration of flooding for higher return period floods. Though there is variation in depths of flooding in upstream and downstream reaches, the duration of flooding are very identical. These computed parameters like flood extent, depth, level, duration and maximum flow velocity are used in designing safe grade levels for the industrial site to safe guard the flood hazard.

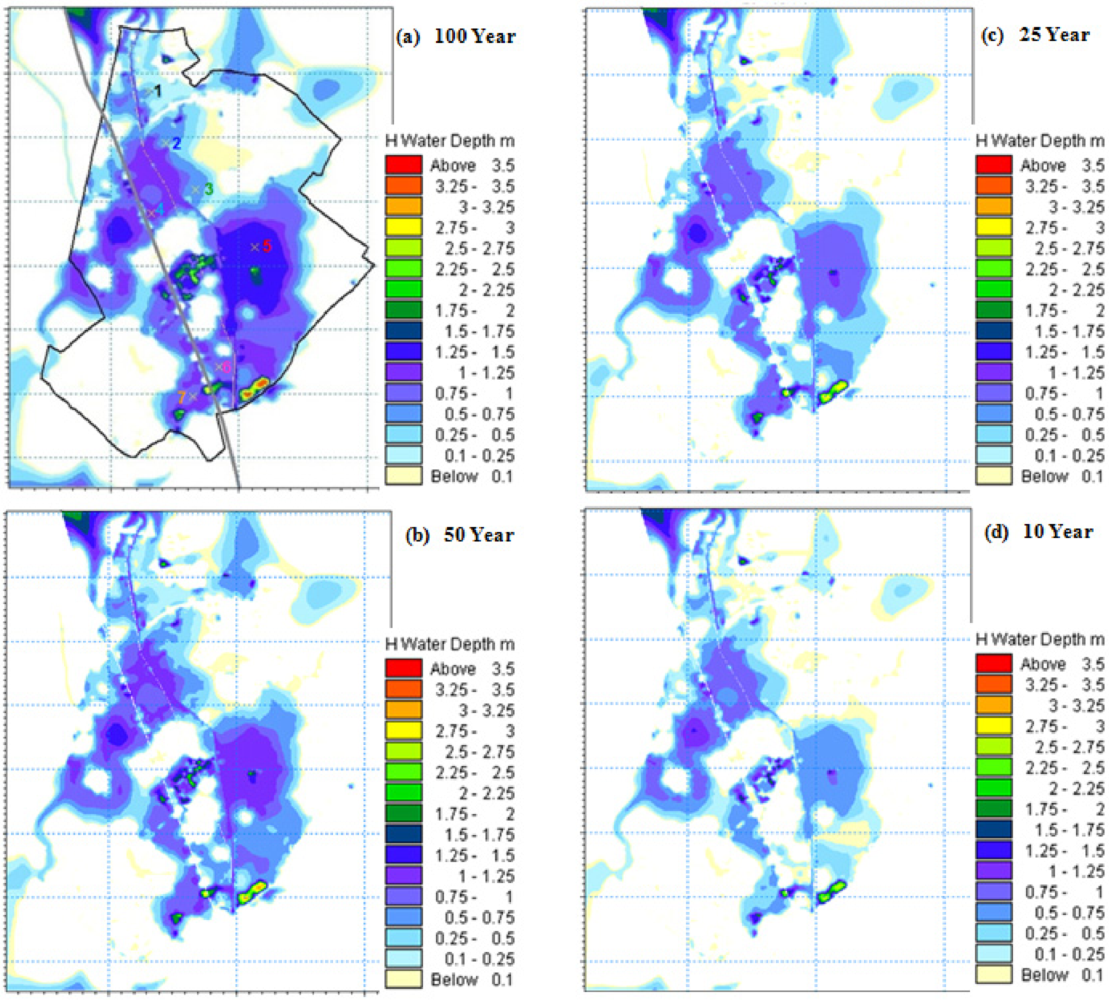

Fig. 6. Flood extent and water depth due to various return period rainfalls.

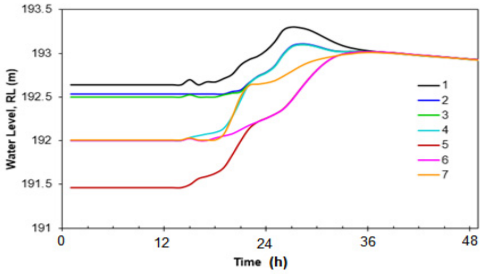

Fig. 7. Water levels at seven grids for 100 year return period flood.

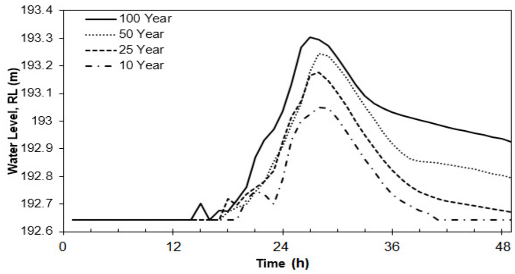

Fig.8. Water levels at grid 1 for various return period flood.

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